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Peak effect in the magnetostriction of superconducting NbTi due to elastic constants

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Abstract

The magnetostriction on polycrystalline superconducting NbTi perpendicular to the field is measured to study lattice deformation effects caused by fluxoids exerting forces on the lattice through pinning centers. A “dip” for increasing and a “peak” for decreasing fields in its length at 80% of the upper critical field ($B_{c2} = 12$ T) was observed. Its temperature dependence is well explained by universal $B_{c2}(T)$ scaling laws for pinning forces and elastic constants. Identical features are observed in the magnetization. In critical current no anomaly is found. An explanation in terms of an anomaly in elastic constants due to a field induced degeneracy of the ground state is discussed.

The basic idea behind a magnetostriction (MS) experiment on a type II superconductor is that a change in field will cause extra forces to act on the fluxoids. These extra forces transmit to the lattice through the pinning centers. An increase in field creates new fluxoids at the samples surface. They will push the already present fluxoids deeper towards the center of the sample. If the time scale of the change of field is big enough for the situation of the fluxoids to be treated as quasi-static, the density of fluxoids (DOF) will be such that the extra compressive forces among fluxoids due to the field increase will be balanced by pinning forces. The DOF will have a decreasing slope going towards the center. See Fig. 1(a). The pinning centers will transmit these compressive forces to the sample. For decreasing fields, a reverse process can be visualized, resulting in a DOF with a increasing slope and an extra expansive forces on the sample. See

Fig. 1(b). Because flux motion is irreversible the magnetostriction curves are expected to display hysteresis.

Polycrystalline NbTi was used, NbTi is related to the A15, BCS-like superconductors. Not to get sidetracked into problems related to different crystallographic directions we used polycrystalline material. It cannot be excluded that the crystallites still have a preferential orientation. Special care was taken to use the material always in the same orientation with respect to the field. As found by magnetization and critical current measurements, its upper critical field $B_{c2}(T)$ and the critical temperature T_c are $B_{c2} = 12$ T (at $T = 4.2$ K), and $T_c = 8$ K (at zero field).

Length changes were measured using a parallel-plate capacitance method. The direction in which the length changes were measured were perpendicular to the field direction. This is the configuration for which the largest effects are to be expected. The field sweeps were never faster than 0.7 T/min. In Fig. 2 some typical MS curves for different fixed temperatures are presented. A “dip” for increasing and a “peak” for decreasing fields is observed

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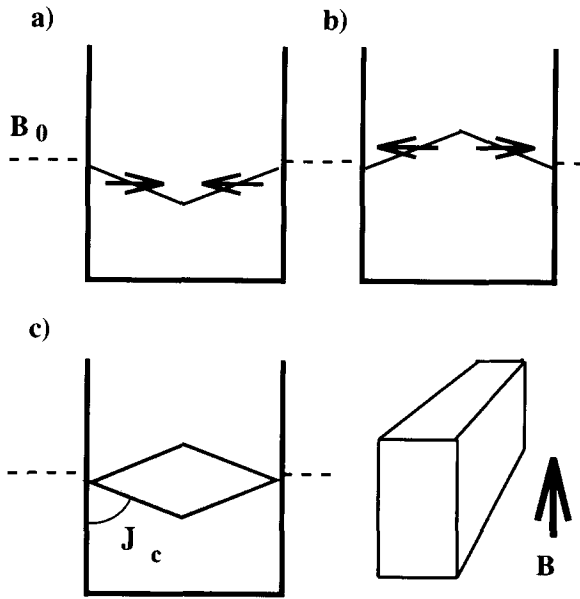


Fig. 1. Slope of the macroscopic field density of fluxoids for: (a) increasing fields, (b) decreasing fields. Dashed area in (c) indicates the difference in magnetization for a field-sweep up-wards and down-wards. J_c =critical current density.

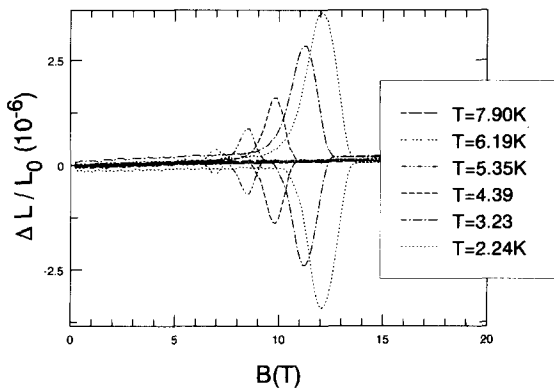


Fig. 2. Magnetostriction $\Delta L \perp B$ for several temperatures. Hysteretic behavior: a “dip” for increasing and a “peak” for decreasing fields.

at 80% of the upper critical field $B_{c2}(T)$ ($B_{\max}(T)$). The hysteretic magnetostriction effect strongly decreases with increasing temperature and is no longer visual at T_c . This anomaly is superimposed on an almost constant background.

Also a magneto-caloric effect was observed. In a different experiment without temperature regulation a peak in the temperature of the sample and the anomaly in the

magnetostriction was simultaneously observed (see Fig. 3). The slight shift in position of the peak between the up- and down-sweep we believe to be related to the thermal constants of the used measurement system.

Overlooking the fact that the macroscopic pinning force density, P_v , the length change, ΔL , are direction dependent, and the elastic constant, c , is a tensor; P_v and ΔL are simply related by $P_v = c\Delta L$. From a macroscopic thermodynamic argument, a modified Ginzburg–Landau description [1], it can be shown that the elastic constant in the super-conducting state at B_{c2} is proportional to the normal state elastic constants times B_{c2}^{-2} : $c(T, B) = c_0(b) B_{c2}^{-2}$, with $b = B/B_{c2}(T)$ and $c_0(b)$ a function depending on b (containing also the normal state elastic constants). It has been observed that in NbTi the macroscopic pinning force density satisfies [2,3] $P_v = [B_c(T)]^{2.5} f(b)$ where $f(b)$ is a function only dependent on b . This indicates that $\Delta L/L_0$ should obey the scaling law; $\Delta L/L_0 = B_{c2}(T)^{4.5} g(b)$, in which $g(b)$ is a function only dependent on b . Assuming $B_{\max}(T)$ always to be a fixed fraction of B_{c2} we plotted $\Delta L/L_0 \times B_{\max}(T)^{4.5}$ as a function of $b = B/B_{\max}(T)$ for different temperatures. See Fig. 4. Indeed the scaling law

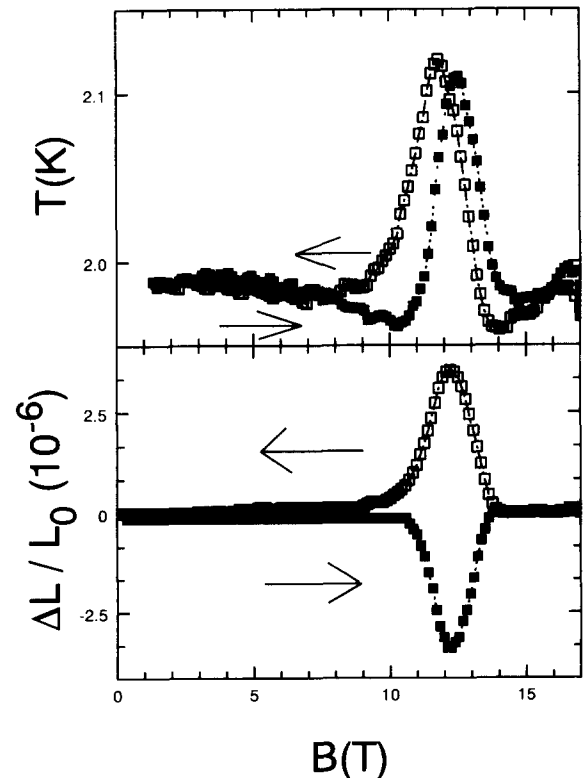


Fig. 3. Magneto-caloric effect: arrows indicate up- or down-sweep.

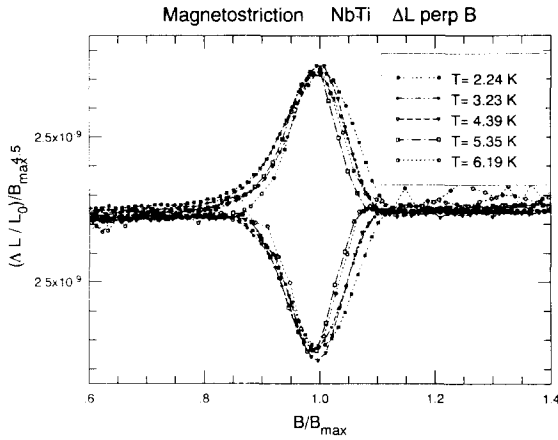


Fig. 4. Scaling law for anomaly in magnetostriction $B_{\max}(T)$ is field at which anomaly is observed.

for $\Delta L/L_0$ seems to be satisfied, suggesting that the origin of the observed anomaly can be either found in the pinning force density or in the elastic constants. The temperature dependence of the MS curves can be interpreted as stemming from the temperature dependence of $B_{c2}(T)$.

Both critical current (CC) and magnetization (MZ) measurements were performed. For the MZ measurements a home built torque magnetometer was used. The observed shape of the MZ curves measured on a disc of 2 mm in diameter and 0.2 mm thickness are identical to the MS curves. If the fluxoids exert a force on the sample (causing the MS), the sample exerts an equal but opposite force on the fluxoids (causing the MZ). The relative change in magnitude of the MZ at the anomaly is in the same order of magnitude as in the MS. This suggests that the anomaly in the MZ could be caused by the MS. Let M be the total MZ, and m the MZ density, then $M = mV$, in which V is the respective volume. Then $M(mV_0) = V/V_0$, in which V/V_0 is related to the MS (V_0 is some reference volume). Our scaling relation between MS and MZ suggest no anomalies to be present in m . By extra cold working of the samples the observed anomaly in the MZ could be considerably increased.

Bean's model basically states that only zero current, in those regions which never felt any magnetic field, or the CC density $J_c(B)$ are possible. Its sense depends on the sense of the electro-motive force that accompanied the last local change of field. The slope of the macroscopic field density related to the DOF, $B(r)$ is related to $J_c(B)$ by Maxwell's relation as $-1/\mu_0 \nabla_r B(r) = J_c(B)$. At the samples edge $B(r = \text{edge})$ is equal to B_0 , in which B_0 is the applied external field. $J_c(B)$ in a certain field can therefore be determined by the difference in MZ, $M(B)$, of an up-sweep, denoted as $M(B)^+$, and a down-sweep, $M(B)^-$

as being proportional to $M(B)^- - M(B)^+$ [4] (see Fig. 1(c)). This suggests that at B_{\max} an enormous peak in $J_c(B)$ occurs. Note how in this argument the elastic constants or the MS are not mentioned.

Finally $J_c(B)$ was measured directly. This was done on the extra cold worked sample (which had the biggest effect in the MZ). See Fig. 5. As a criterion for the CC density $1 \mu\text{V}/\text{cm}$ was used. The cross-section of the used strip was so small ($0.2 \times 0.5 \text{ mm}^2$) that the DOF can be assumed as being constant and not being V-shaped as in the MS and MZ experiments. Therefore the net force of the fluxoids on the strip is negligible, no MS effects are to be expected. This was confirmed by not observing any hysteresis effects in the CC.

Only a very small feature is observed at B_{\max} . $P_r(B)$ and $J_c(B)$ are intimately related by $P_v = B \otimes J_c(B)$ [4,5]. Indicating that the anomaly observed in the MS is not so much caused by a peak in the pinning force density but moreover by a sudden softening of the elastic constants. The discrepancy with $J_c(B)$ as derived from MZ data can possibly be ascribed to the fact that we did not consider the elastic constants in our analysis of the MZ data.

NbTi is related to the A15 superconductors. Peaks in the density of states at the Fermi level are present. Suppose the field effect is different for the electronic properties parallel to the field from those perpendicular to it, it is imaginable that by tuning the field, more than two-fold degenerate ground state is created. This will cause a field induced Jahn-Teller effect with delocalized states. The sample deforms itself in the direction of the already present forces, possibly explaining the combination of observed features in MS, MZ and CC.

In conclusion; we observed an identical hysteretic anomaly at B_{\max} in both MS and MZ. The temperature

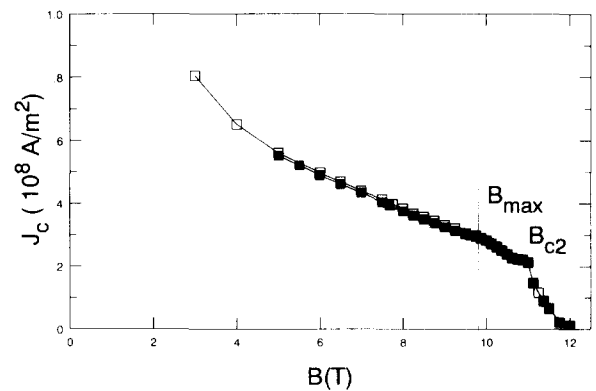


Fig. 5. Critical current: B_{c2} = upper critical field, B_{\max} = field at which anomaly in magnetostriction is observed. Closed symbols: measured in increasing field. Open symbols: measured in decreasing field.

dependence of the observed MS effect is well explained by a combination of universal $B_{c2}(T)$ scaling laws for pinning forces and elastic constants. The observed effect should therefore be caused by an anomaly in either the pinning forces or the elastic constants. In a CC measurement almost no anomaly was found at B_{\max} . Since the CC is directly related to the pinning force density, we concluded that the observed effect in the MS was due to an anomalous softening of the elastic constant. The discrepancy between MZ and CC measurements was explained in terms of the strong volume changes. In the CC experiment no forces are exerted on the sample since in this configuration no gradient in the DOF is present (unlike in the MS- and MZ-experiment). The relative change at the anomaly in MS- and MZ is in the same order of magnitude. An attempt was made to explain this in terms

of an anomaly in the elastic constants due to a field-induced degenerate ground state. The observed magneto-caloric effect is related to the dissipative processes involved in flux movement.

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